HOT-ELECTRON BOLOMETER MIXERS FOR SUBMILLIMETER WAVELENGTHS: AN OVERVIEW OF RECENT DEVELOPMENTS

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INTRODUCTION

In the past couple of years there has been a resurgence of interest in bolometers as heterodyne mixers at submillimeter wavelengths. This is due primarily to two new, and different, innovative concepts [1,2] which result in bolometers with response times fast enough to allow for intermediate frequencies (IF) of 1 GHz - 10 GHz, as well as low mixer noise temperatures. These IF's are high enough for practical spectroscopy applications and thus these bolometers need to be seriously considered as heterodyne sensors. In this paper I will review briefly review the basics of bolometer mixers. Then an overview will be given of the basic operation of the new high speed bolometers. The advantages and potential limitations of each approach will be discussed. A few recent results which demonstrate the performance will be given. Finally, the role these sensors may be expected to fulfill will be discussed. I should emphasize that this paper is meant to provide an introduction to these new bolometer mixers, and reference will be made to the recent literature for the interested reader who wishes to delve more deeply into the details. However, this is not a review article, but rather an overview of recent developments, so no attempt is made to give a complete listing of results and publications.

BOLOMETER MIXERS

Bolometers have been used occasionally over the years as heterodyne mixers. This is because bolometer mixers have several important advantages: 1) High frequency operation: bolometers can be designed and optimized to work at millimeter wavelengths, submillimeter wavelengths, and of course, on out to infrared wavelengths and beyond. 2) Bolometers can have very high sensitivity and near-quantum limited noise. 3) Bolometers are simple square-law or total power detectors. There is no instantaneous response at the rf as with an electronic mixer, such as a Schottky diode or SIS tunnel junction. There is also no harmonic response. The principle disadvantage of the bolometer mixer is the slow thermal response time. This limits the IF to low values, usually of order MHz. In general this is too low to be useful for many remote-sensing applications involving molecular line spectroscopy such as radioastronomy, atmospheric chemistry, and planetary science. The limitation placed on the IF by the thermal response time can be understood by considering the basic operation of a bolometer mixer as discussed below.

The two basic elements of a bolometer are shown in figure 1. There is an element which absorbs the incident rf power. This can be an absorbing film or other lossy material. The absorber has a thermal heat capacity C, and as it absorbs power its temperature T increases. The absorber is connected to a thermal bath temperature T_{bath} by a thermal conductance G. The thermal response time is given by $\tau_{th} = C / G$, and represents the characteristic time over which the temperature of the bolometer can change for a sudden change in incident rf power.
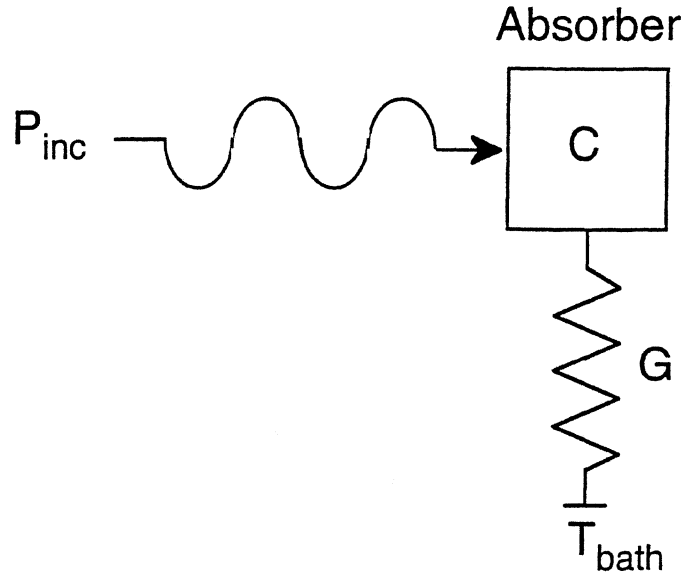
Absorber

Fig. 1: Basic elements of a bolometer. C is the heat capacity of the absorber, typically a thin film. G is the thermal conductance to the bath temperature. P_{inc} is the incident rf power.

To operate the bolometer in a heterodyne mode, a local oscillator (LO) voltage at frequency ω_{LO} and a signal voltage at frequency ω_s are applied to the absorber:

$$V(t) = V_{LO} \cos (\omega_{LO} \, t) + V_s \cos (\omega_s \, t) \tag{1}$$

For simplicity, we take the absorber to be a thin resistive film of total resistance R_n. Then the power dissipated in the film is:

$$P(t) = V(t)^2 / R_n \tag{2}$$

Substituting eqn (1) into eqn (2) yields:

$$P(t) = P_{LO} + P_s + 2(P_{LO} \, P_s)^{1/2} \cos(\omega_{IF} \, t) \tag{3}$$

where $\omega_{IF} = \omega_{LO} - \omega_s$ is the IF frequency, and $P_{LO} = (V_{LO}^2 / 2R_n)$ and $P_s = (V_s^2 / R_n)$ are the LO power and signal power respectively dissipated in the bolometer. The bolometer is not fast enough to follow the rf, so the power dissipated at these frequencies is the time averaged value. However, if the IF is low enough, the bolometer can follow this variation, so there can be a time dependent term at this frequency. The *Voltage Responsivity*, S, of the bolometer [3] gives the change in voltage across the bolometer for a change in absorbed power, and hence can be used to estimate the IF voltage amplitude:

$$V_{IF} = S \cdot 2(P_{LO} \, P_s)^{1/2} \tag{4}$$

The responsivity is given by:

$$S = I \, (dR \, / \, dT) \, / \, [G \bullet (1 + \omega_{IF}^2 \, \tau_{th}^2)^{1/2}] \qquad (5)$$

where I is the bias current through the resistive film, and dR/dT is the derivitive of film resistance with temperature. Thus for low enough IF, that is $\omega_{IF}^2 \tau_{th}^2 < 1$, the bolometer can follow the IF power swing; but for $\omega_{IF}^2 \tau_{th}^2 > 1$, the IF voltage will decrease and hence the conversion efficiency of the mixer will decrease. As mentioned above, τ_{th} for many conventional bolometers is long enough that the IF is limited to undesirably low values. However, the two new bolometer concepts discussed below address this issue.

NEW APPROACHES

Recently, two new approaches [1,2] have been proposed for bolometers with very short thermal response times and hence a high IF rolloff frequency. Both bolometers utilize the resistive transition in a superconductive thin film which results in a large dR/dT and hence high responsivity. What is new however, is that these devices make use of very thin films: about 10 nm for Nb or NbN. Such thin films have a very high scattering rate due to surface effects and hence a short electron mean free path ℓ, which is about 1 nm - 10 nm. In these films, it is found that the electron-electron interaction is enhanced, resulting in a short electron-electron interaction time: $\tau_{ee} \propto \ell$; and the electron-phonon interaction is weakened: $\tau_{ep} \propto \ell^{-1}$ [2]. Hence the electrons can reach thermal equilibrium at a temerature different from the lattice temperature. Thus when absorbing rf power, the electrons can warm up relative to the lattice temperature. The electrical resistance in the film depends on the electron temperature and such a device is known as a hot-electron bolometer. Since only the electrons are heated, the heat capacity C can be very small, especially for a submicron-sized device. In addition, the hot-electron bolometer mixers discussed below employ novel mechanisms for cooling the electrons which results in a high thermal conductance and hence an overall short thermal relaxation time.

Before describing the details of the bolometers, it is useful to list the important advantages of these novel devices:

1) The thermal response time is very fast: $\approx$ 10's ps. Thus IF's of 1 GHz - 10 GHz can be achieved.

2) These bolometer mixers should operate well to very high frequency: several THz. There is no energy gap limitation as in an SIS mixer. In fact, rf power is absorbed more uniformly above the energy gap frequency.

3) The mixer noise temperature is very low: near-quantum limited.

4) Very low LO power is required: nW's - μW's. This is comparable to the requirements for SIS mixers and is an important issue at high submillimeter wave frequencies where LO power is difficult to generate.

5) The rf impedance of the device is esentially resistive and is determined by the geometry of the film; that is, the number of squares in a small strip. Typical values range from 20 Ω to 200 Ω. This greatly simplifies the rf circuit design. Unlike a Schottky diode or SIS

tunnel junction, there are no parasitic reactances to tune out. The real rf resistance of the bolometer should be independent of frequency from about the energy gap frequency up to a frequency corresponding to the inverse electron-electron elastic scattering time (about 10^{-15} sec) which is approximately 160 THz.

6) In addition, these devices make use of existing materials and fabrication techniques: Nb, NbN, YBCO; micron-scale photolithography, and/or submicron E-beam lithography.

DIFFUSION-COOLED HOT-ELECTRON BOLOMETER MIXER

Figure 2 shows the basic geometry of this bolometer mixer which was proposed by D. Prober in 1993 [1]. The unique feature of this device is that it uses the rapid diffusion of hot electrons out of a submicron length strip of superconductor (or microbridge) into normal metal contacts as the cooling mechanism, or thermal conductance. In order for diffusion to dominate, over electron-phonon interactions, as the cooling mechanism, it is necessary for the microbridge to be short. The appropriate length L can be estimated from the expression:

$$L \approx 2 (D \ \tau_{ee})^{1/2} \tag{6}$$

where D is the diffusion constant, and τ_{ee} is the electron-electron inelastic ("energy sharing") interaction time. Basically when an electron absorbs energy from an rf photon, it shares its energy in a time τ_{ee} and also diffusies a distance L/2. A hot electron in the middle of the bridge can thus go L/2 left or right. At that point, it encounters the normal metal contact which serves as a heat sink. These pads at the end of the microbridge must be normal metal since Andreev reflection [4] at the energy gap in a thick superconducting film would trap the hot-electrons inside the microbridge and substantially slow the response of the device. The electron-electron interaction time can be estimated from [5]:

$$\tau_{ee} \approx (10^8 \ R_s \ T_c)^{-1} \tag{7}$$

where R_s is the surface resistance and T_c is the transition temperature of the thin film. For the very thin (dirty limit) film used here, R_s is larger and T_c is smaller than the bulk values. For a 10 nm Nb film for example, $R_s \approx 20 \ \Omega/sq$, $T_c \approx 5$ K, and the width of the transition is $\Delta T_c \approx$ 0.5 K. Substituting these values into eqn (6) and eqn (7), yields a length $L \approx 0.2 \ \mu m$. The microbridge can be somewhat longer (with a corresponding increase in τ_{th}), but should be less than $2(D \ \tau_{ep})^{1/2}$ where τ_{ep} is the electron-phonon interaction interaction time. For this length and longer the electrons will remain in the bridge long enough to produce phonons which can then warm the lattice and slow the device response time.

The thermal response time can be calculated from the usual expression:

$$\tau_{th} = C / G \tag{8}$$

The thermal capacitance is given by the electron specific heat [6]:

$$C = \gamma T V \tag{9}$$

$$P_{inc}$$

Normal
Metal

Normal
Metal

$$(2\Delta = 0)$$

L

Nb Microbridge
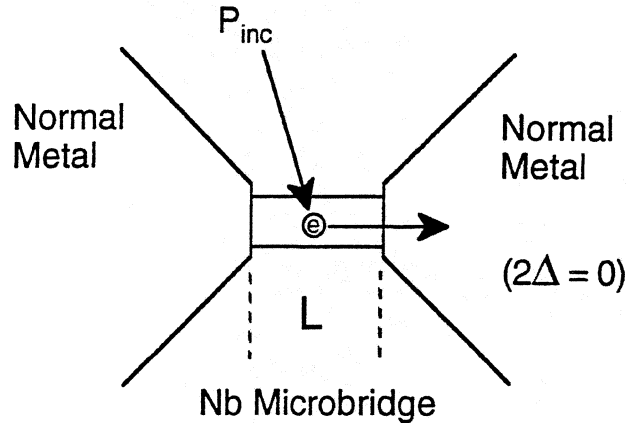
Fig. 2: Basic geometry of the diffusion-cooled hot-electron
bolometer mixer.

where $\gamma = 700$ J/K^{2}m^3 for Nb, T is the electron temperature (which is always about T_c in a transition edge device), and V is the device volume. The thermal conductance G is given by the Wiedemann-Franz Law [6]. This law states that the ratio of thermal conductance to electrical conductance is proportional to temperature, if the electrons carry both the electrical current and the thermal current, which is the case for the diffusion-cooled microbridge. Thus:

$$G = (\pi^2/3) (k_B / q_e)^2 (T / R_{eff}) \tag{10}$$

where k_B is Boltzman's constant, q_e is the charge on the electron, T is the temperature ($\approx T_c$) and R_{eff} is the effective electrical resistance of the microbridge: $R_{eff} \approx R_n / 12$ [1]. R_n is the DC resistance of the microbridge for $T > T_c$, or equivalently it is the rf resistance for frequencies above the gap frequency. The factor 1/12 arises because heat flows symmetrically out both ends of the microbridge.

For an actual bridge [7] with dimensions width = 0.14 μm, length = 0.28 μm, thickness = 0.01 μm and $R_n = 30 \Omega$, the estimated response time is 30 psec. The 3 dB IF rolloff frequency for the mixer gain is then given by:

$$\text{IF}_{rolloff} = (2 \cdot \pi \cdot \tau_{th})^{-1} \tag{11}$$

which is about 5 GHz in this case. However, due to self-heating effects [3] (and to a lesser extent by IF impedance mismatch effects [8]) the thermal conductance is reduced to a lower effective value:

$$G_{eff} = G (1 - A) \tag{12}$$

where typically $0.1 < A < 0.9$ for thermally stable operation. Thus the value of IF$_{rolloff}$ can actually be in the range of about 2-5 GHz. This allows for an IF commonly used in heterodyne instruments.

Now we will estimate the mixer conversion efficiency η, the double-sideband receiver noise temperature T_R(DSB), and the LO power P_{LO} following the approach given by

Prober [1]. The conversion can be estimated using the voltage responsivity of the bolometer and the IF power amplitude. The result is:

$$\eta = P_{IF} / P_{rf} = [\, I^2 \, (dR/dT)^2 / G^2 \,] \bullet [\, P_{LO} / 2R \,] \tag{13}$$

(note that this expression is valid for $\omega_{IF}\, \tau_{th} < 1$, otherwise there would be another factor of $[1 / (1 + \omega_{IF}^2\, \tau_{th}^2)]$ multiplying the above expression). For equal DC power ($P_{DC} = I^2R$) and LO power dissipated in the bolometer, then $\eta(SSB) = 1/8 = -9$ dB (see references 8 and 9 for a detailed formulation of bolometer-mixer conversion efficiency). It can be shown that the conversion efficiency in this case is independent of L, the length of the microbridge [1]. However, the response time $\tau_{th} \propto L^2$, thus $IF_{rolloff} \propto 1 / L^2$. Hence, as expected for a device that relies on diffusion out the ends, shorter is better for high speed. However, there is no sacrifice in conversion efficiency. While decreasing L will increase G and hence reduce the bolometer responsivity, in the heterodyne mode this can be compensated by increasing the LO power. Thus it is possible to have a bolometer mixer which is both *fast* and *sensitive*.

The LO power can be readily approximated by:

$$P_{LO} \approx \Delta T_c\, G \tag{13}$$

This expression simply states that enough LO power must be applied to increase the temperature of the bolometer up through the range of ΔT_c, the temperature range over which the resistance of the bolometer varies strongly. In practice, the bolometer is thermally biased at a temperature somewhat below Tc, then a combination of DC and LO power is used to heat the electrons up to T_c. The best optimization of DC and LO power is a topic of current discussion (see reference 10, for example), but eqn(13) gives a good first-order estimate. (Actually, since the typical operating temperature is about T_c which is in the middle of the range ΔT_c, the required LO power may be 1/2 to 1/4 of the value given by eqn(13)). For the Nb bolometer discussed here, the required LO power is about 10 nW: a very low value.

It is currently accepted that the main contributions to the noise in a bolometer mixer are due to Johnson noise and electron temperature fluctuation noise [11]. The latter being dominant. The Johnson noise temperature is, of course, T_c and arises from the film resistance at the transition temperature. The electron temperature fluctuation noise arises from the thermodynamic energy fluctuations in an electron gas at an average thermodynamic temperature T_c. The RMS electron temperature fluctuation can be expressed as [8]:

$$\Delta T_e = 4\, k_B\, T^2 / G \tag{14}$$

The resulting DSB receiver noise temperature can be expressed as [1]:

$$T_R\,(DSB) = [\, (\, T_c^2 / \Delta T_c) + T_c + T_{IF} \,] / \eta \tag{15}$$

where T_{IF} is the IF amplifier system noise temperature. Thus for $T_c = 5$ K, $\Delta T_c = 0.5$ K, $T_{IF} = 4$ K, and $\eta(DSB) = -7$ dB (ie: 6 dB intrinsic mixer conversion loss and 1 dB of receiver optical path loss), we get $T_R(DSB) = 295$ K. However, reducing T_c just 1 K (a slightly thinner film) yields $T_R(DSB) = 200$ K. This performance becomes competitive with current state-of-the-art SIS receivers near frequencies of 500 GHz - 600 GHz. However, for the bolometer mixer there is no inherent frequency dependence of the performance above the

energy gap frequency (except of course for the linear frequency dependence set by the quantum limit [12]). The same noise temperature, 200 K, should be possible at 0.5 THz or several THz (mechanisms which may ultimately limit the high frequency performance will be briefly discussed below).

To date, the diffusion-cooled hot-electron bolometer mixer has been rapidly developed by the Jet Propulsion Laboratory in collaboration with Yale University [7,13] (no other groups have yet reported results on this new device). Figure 3 shows an SEM photo of a Nb bolometer with a length of 0.28 μm. In fig. 4, a typical resistance-vs-temperature curve shows T_c and ΔT_c. These bolometers were tested in a waveguide mixer mount in a receiver at an LO frequency of 530 GHz (see references 7 and 14 for a complete discussion of these results). This LO frequency is well above the gap frequency of $\approx$ 390 GHz for this thin Nb film with $T_c \approx$ 5 K. The DSB receiver noise temperature is 650 K at an IF of 1.4 GHz. The estimated DSB mixer noise temperature is 560 K and mixer conversion efficiency is about -11 dB. The predicted receiver noise temperature is 570 K - 750 K (depending on the exact choice of ΔT_c from the R-T curve), and similarly the predicted mixer conversion efficiency efficiency is about -10 dB to -15 dB. Thus the calculated values agree well with experiment. The IF rolloff frequency was measured to be about 2 GHz, making this the fastest bolometer ever reported. It is thus clear from these results that this device works well as a submillimeter wave heterodyne mixer.
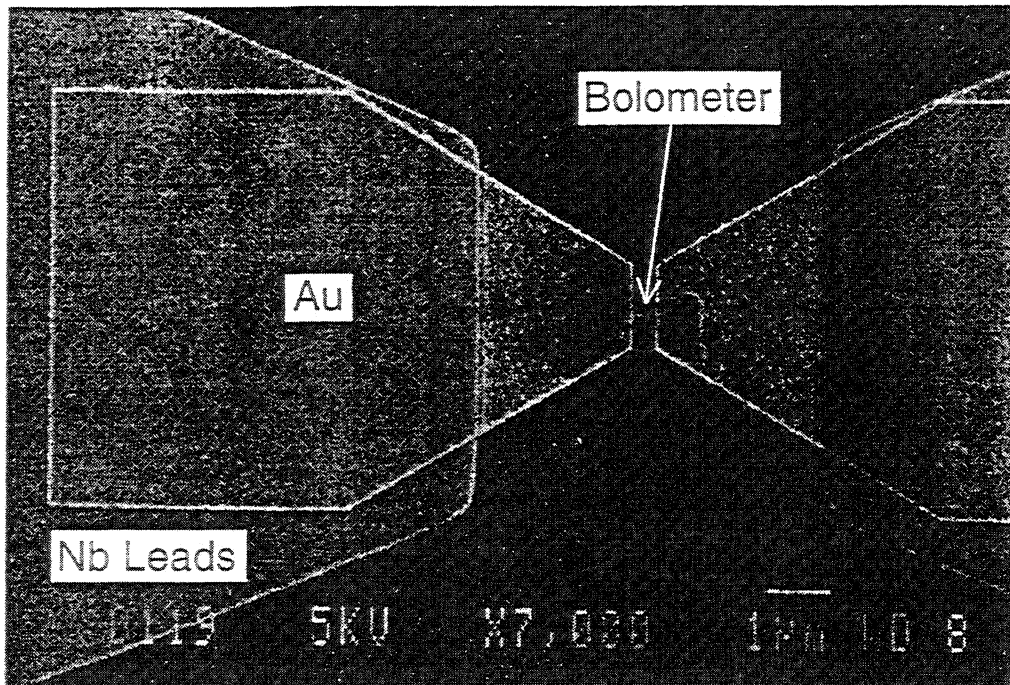

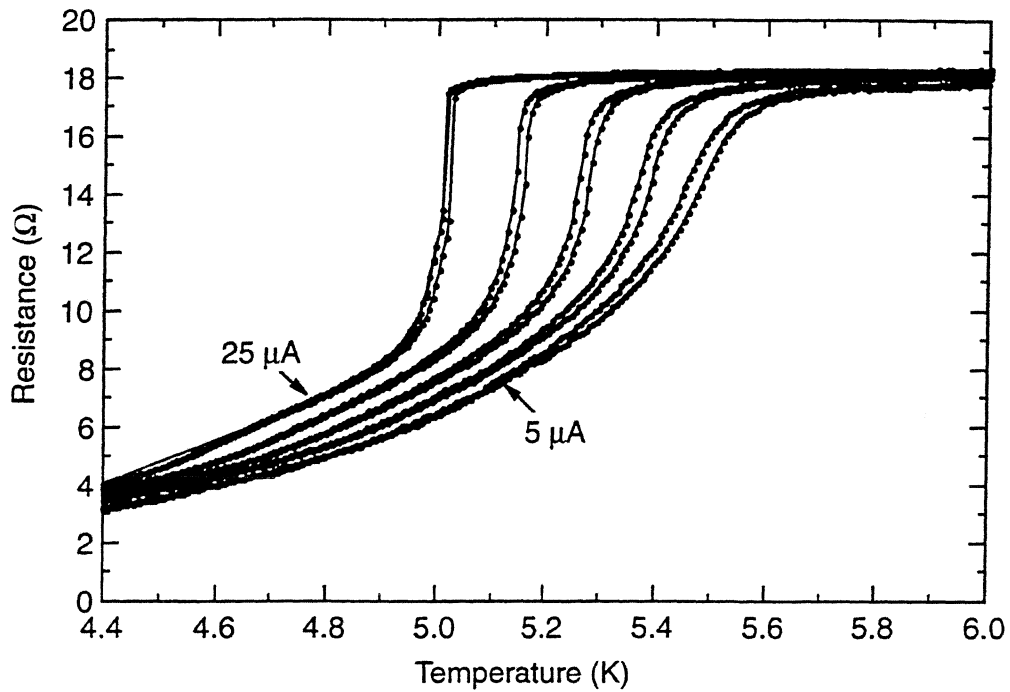Fig. 3: SEM photo of a diffusion-cooled bolometer mixer.

Fig. 4: Resistance versus temperature for a Nb microbridge. The different curves are for different DC currents through the device to measure its resistance. The resistive transition sharpens due to self-heating by the larger currents. The Tc is around 5.4 K and the width is about 0.5-1 K (see 5 μA curve)

ELECTRON-PHONON COOLED HOT-ELECTRON BOLOMETER MIXER

Figure 5 shows the basic geometry of this bolometer which was proposed by E. Gershenzon, et al in 1990 [2]. The geometry is similar to the diffusion-cooled bolometer except that it does not use normal metal at the ends of the microbridge since it employs electron-phonon interactions to the substrate, rather than diffusion to out the ends, to cool the hot electrons (perhaps it is more correct to say that the geometry of the diffusion-cooled bolometer resembles the electron-phonon cooled bolometer since it was proposed first). The basic operation of this bolometer can be understood from fig. 5(b). An incident rf photon imparts its energy to an electron in the film. In a short time τ_{ee} this electron shares its energy with other electrons. The cumulative effect of absorbed rf power and the energy sharing process (ie: the enhanced electron-electron interaction) in these ultra-thin films is to create a hot-electron distribution. Then in a time τ_{ep} a hot electron creates a phonon which then escapes ballistically, for a sufficiently thin film, to the substrate in a short time τ_{ES}. In order for the hot-electron bolometric mechanism to proceed in this manner, there are some constraints which must be met. First $\tau_{ee} \ll \tau_{ep}$ to allow the electrons to heat up from absorbed power. This is usually satisfied for a thin (dirty limit) film at low temperatures $T < 10$ K ($\tau_{ee} \approx 10^{-10}$ sec to 10^{-12} sec) [15]. Next it is important for $\tau_{ES} \ll \tau_{pe}$, where τ_{pe} is the phonon-electron interaction time . That is, the phonons must escape to the substrate before they interact back with other electrons. This requires that the film be very thin since[2,15,16]:

$$\tau_{ES} = 4 \, d \, C_e / (\, v \, \alpha \, C_{ph}) \tag{16}$$

where d is the film thickness, C_e and C_{ph} are the electron and phonon specific heats respectively, v is the velocity of sound, and α is the coefficient of transmission of a phonon through the film-substrate interface. The thermal response time of the bolometer can then be written as:

$$\tau_{th} = \tau_{ep} + \tau_{ES} \tag{17}$$

Thus the limiting speed of this type of bolometer is set by τ_{ep} (this limit requires $\tau_{ES} \ll \tau_{ep}$ and thus the films should be thin, the phonon transmission at the substrate interface high, and the thermal conductivity of the substrate should also be high so that it remains a constant temperature bath). This electron-phonon thermal response time can be estimated from C/ G where $C = \gamma \, T \, V$ is the electron specific heat (see eqn (9)) and:

$$G = 4 \, A \, T^3 \, V \tag{18}$$

is the phonon thermal conductance (A is a constant $\approx 10^4$ W cm^{-3} K^{-4} for thin Nb films [2]) Thus [17]:

$$\tau_{ep} = \gamma / (4 \, A \, T^2) \tag{19}$$

For a Nb bolometer, $\tau_{ep} \approx 1$ ns and hence $IF_{rolloff} \approx 160$ MHz, which is higher than most bolometer mixers but still too low for many practical applications. For NbN operated at 7 K - 8 K, $\tau_{ep} \approx 15$ ps and hence $IF_{rolloff} \approx 10$ GHz. This is of course high enough to be of practical value.
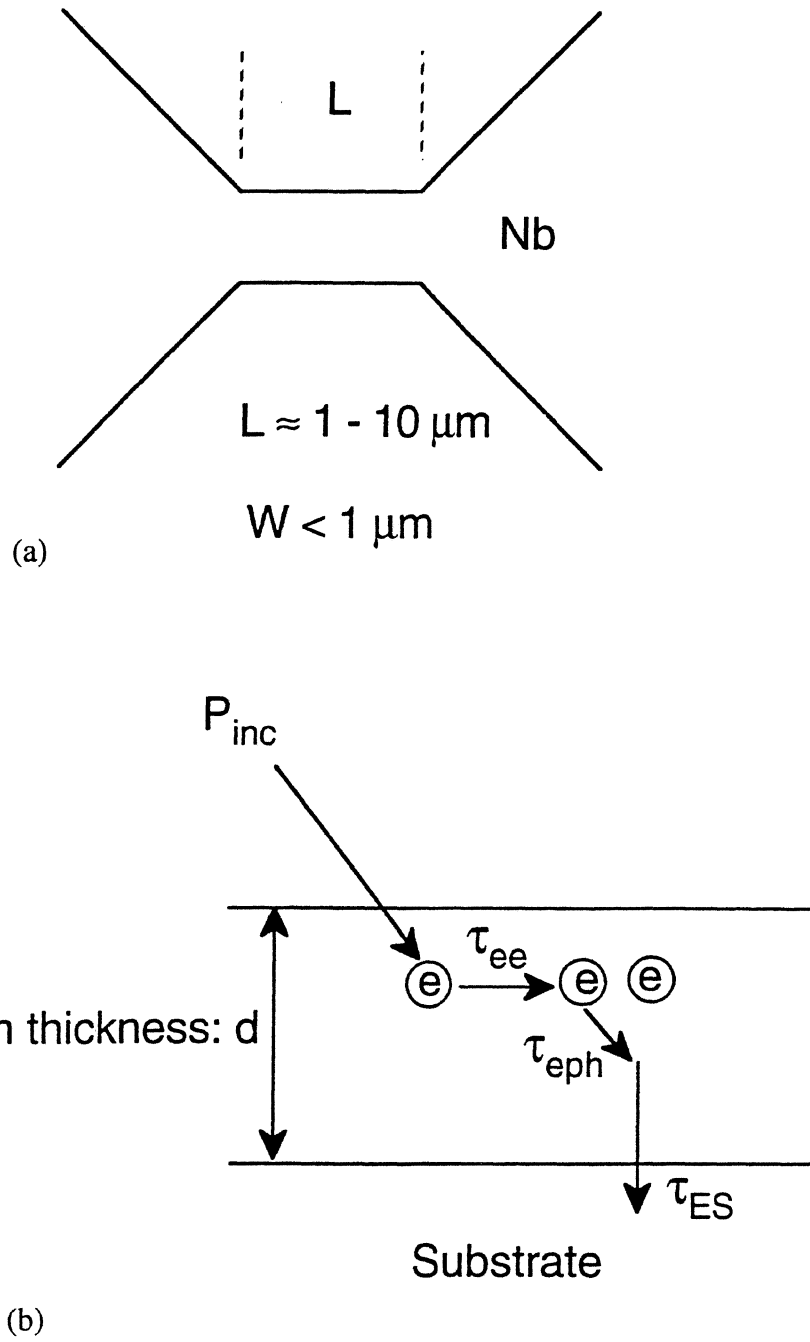
Fig. 5: Basic geometry of electron-phonon cooled bolometer mixer. (a) Top view showing geometry of microbridge. (b) cross sectional view showing schematically the electron-phonon interactions described in the text.

The LO power requirements can be estimated in the same way as for the diffusion-cooled bolometer mixer using eqn. (13), except G is now given by eqn.(18). It should be noted that G in this case depends on the volume of the microbridge and thus it is advantageous to keep the volume small. The width of the microbridge should be less than about 1 μm to avoid a backflow of phonons from the substrate [2]. Then for a given film surface resistance R_s the length is chosen to give the appropriate resistance for an rf match to the mixer embedding circuit (waveguide, planar antenna, etc...). A typical size is 1 μm x 5 μm. The LO power then required for a Nb bolometer mixer is about 50-70 nW ($T_c = 4$ K and $\Delta T_c = 0.5$ K); and for NbN, $P_{LO} \approx 0.5$-1 μW ($T_c = 7$ K and $\Delta T_c = 0.5$ K). These are extremely low and therefore very desirable for submillimeter operation.

The mixer noise temperature and conversion efficiency are calculated in the same way as for the diffusion-cooled bolometer mixer. However, the more detailed analysis in [8] suggests that under certain conditions, conversion efficiency greater than unity is possible. Also, as mentioned above, the exact choice of DC and LO power to optimize the mixer is still being theoretically analyzed.

Recent results have shown that the electron-phonon cooled bolometer mixer performs very well. Measurements on a Nb bolometer mixer [8] at an LO frequency of 20 GHz gave conversion efficiencies between -1 dB and -7 dB, an IF rolloff of 80-100 MHz, and an LO power of about 40 nW. These results are in close agreement with expected values. The noise measurements were less certain, but gave a DSB mixer noise temperature of 80 K - 450 K. This may seem high for 20 GHz, but it should be kept in mind that the performance should be independent of frequency, and thus this would be excellent performance at submillimeter wavelengths. Measurements on an NbN bolometer mixer at 100 GHz [18] gave $\eta = -10$ dB, $IF_{rolloff} \approx 700$ MHz to 1 GHz, $T_R(DSB) \approx 1000$ K, and $P_{LO} \approx 1$ μW. This is also good performance, except that the IF rolloff is somewhat lower than might be expected. This is probably due to the fact that the phonons did not readily escape into the substrate due to a poor film-substrate interface. This issue is currently being addressed; see the NbN bolometer mixer papers in this conference proceedings for the latest results.

DISCUSSION

The recent innovations in transition-edge hot-electron bolometers (micron and submicron sized, thin, dirty films) have led to ultra-fast, sensitive devices which are competitive as heterodyne mixers. Recent measurements (see particularly this conference proceedings) have proven the concepts and even shown competitive performance. However, the measurement to date have been mainly below 1 THz (there are some recent results on a high-Tc YBCO hot-electron bolometer mixer at an LO wavelength of 1.8 μm [19], but I have not discussed them here) where there already exist state-of-the-art SIS receivers with very low noise. These new bolometer mixers will play an important role at frequencies well above 1 THz where SIS and Schottky receivers become either extremely difficult or impossible (ie: above the energy gap frequency of NbN for example) to operate. In addition, a high-Tc version will be useful in applications where sensitivity can be traded off against cooling requirements, as in a space-based mission.

Important development issues must be addressed for each bolometer. The diffusion-cooled bolometer will need improved submicron definition and alignment of the normal metal contacts. Also, low-resistance normal-to-superconductor contacts are required. For the electron-phonon cooled bolometer, the phonon reflection at the film substrate interface must be minimized. This will be particularly important for materials like NbN (which have a high

upper limit to the IF rolloff) which can react strongly with common rf substrates such as quartz, thereby producing a poor interface. In addition, both types of bolometers are resistive at the rf, so a very broadband match, to a planar antenna for example, should be easily achieved. The rf bandwidth can however be so broad that the mixer will be easily saturated. Unlike the common situation for an electronic mixer with reactive parasitics where the goal is to achieve a broadband rf match, these bolometer mixers may require band-limiting rf filters.

Finally, since the likely role for these bolometer mixers will be at very high frequencies, it is important to test as soon as possible the prediction that the performance is independent of frequency. If they do not perform well at frequencies beyond a THz, their application may be limited. Certain mechanisms may affect the high frequency performance. A high energy rf photon (several THz) will produce a high energy electron in the superconductive film. This hot electron can then either share its energy with other electrons, or break Cooper pairs, or produce hot phonons. In any case, the film will absorb rf power, but if the energy escapes, for example by the hot phonons rapidly leaving the film, before it is shared with the electron gas, then the electrons will not heat as efficiently and the sensitivity of the mixer will decrease. The expectation is that the performance will not degrade until at least several THz. Assuming this is true, these detectors should have a significant impact on the field of THz heterodyne sensors.

ACKNOWLEDGEMENTS

REFERENCES

[1]   D.E. Prober, "Superconducting terahertz mixer using a transition-edge microbolometer", Appl. Phys. Lett. 62 (17), pp. 2119-2121 (1993).

[2]   E.M. Gershenzon, G.N. Golt'sman, I.G. Gogidze, Y.P. Gusev, A.I. Elantev, B.S. Karasik, A.D. Semenov, "Millimeter and submillimeter range mixer based on electronic heating of superconductive films in the resistive state", Superconductivity 3 (10), pp. 1582-1597 (1990).

[3]   P.L. Richards, "Bolometers for infrared and millimeter waves", J. Appl. Phys. 76, pp. 1-23 (1994).

[4]   A.F. Andreev, Sov. phys. JETP 19, 1228 (1964).

[5]   P. Santhanam and D.E. Prober, "Inelastic electron scattering mechanisms in clean aluminum films", Phys. Rev B 29, pp. 3733-3736 (1984).

[6]   C. Kittel, *Introduction to Solid State Physics,* 5th edition, John Wiley & Sons, Inc. New York (1976).

[7]   A. Skalare, W.R. McGrath, B. Bumble, H.G. LeDuc, P.J. Burke, A.A. Verheijen, D.E. Prober, "A heterodyne receiver at 533 GHz using a diffusion-cooled superconducting hot electron bolometer mixer", to appear in IEEE Trans. Appl. Superconductivity (March 1995).

[8]   H. Ekstrom, B. Karasik, E. Kollberg, K.S. Yngvesson, "Investigation of a superconducting hot electron mixer", Proc. 5th Int'l. Symp. on Space Terahertz Technology, Univ. of Michigan, pp. 169-188 (1994).

[9]   F. Arams, C. Allen, B. Peyton, E. Sard, "Millimeter mixing and detection in bulk InSb", Proc. IEEE 54, pp. 308-318 (1966).

[10] B.S. Karasik and A.I. Elantev, "Analysis of the noise performance of a hot-electron superconducting bolometer mixer", This conference proceedings.

[11] J.C. Mather, "Bolometer noise:nonequilibrium theory", Appl. Optics 21, p.1125 (1982).

[12] C.M. Caves, Phys. Rev D 26, p. 1817 (1982).

[13] A. Skalare, W.R. McGrath, B. Bumble, H.G. LeDuc, P.J. Burke, A.A. Verheijen, D.E. Prober, "A superconducting hot-electron bolometer mixer for 530 GHz", Proc. 5th Int'l. Symp. on Space Terahertz Technology, Univ. of Michigan, pp. 157-168 (1994).

[14] A. Skalare, W.R. McGrath, B. Bumble, H.G. LeDuc, P.J. Burke, A.A. Verheijen, D.E. Prober, "Noise temperature and IF bandwidth of a 530 GHz diffusion-cooled hot-electron bolometer mixer" This conference proceedings.

[15] E.M. Gershenzon, M.E. Gershenzon, G.N. Gol'tsman, A.M. Lyul'kin, A.D. Semenov, and A.V. Sergeev, "On the limiting characteristics of high-speed superconducting bolometers", Sov. Phys. Tech. Phys. 34, pp. 195-201 (1989).

[16] G.N. Gol'tsman, A.I. Elant'iev, B.S. Karasik, and E.M. Gershenzon, "Antenna-coupled superconducting electron-heating bolometer", unpublished.

[17] E.M. Gershenzon, G.N. Gol'tsman, B.S. Karasik, G.Ya. Lugova, N.A. Serebryakova, and E.V. Chinkova, "IR radiation detectors based on electronic heating of films made from conventional superconductors in the resistive state", Superconductivity 5, pp.1126-1137 (1992).

[18] O. Okunev, A. Dzardanov, H. Ekstrom, S. Jacobsson, E. Kollberg, G. Gol'tsman, and E.M. Gershenzon, "NbN hot electron waveguide mixer for 100 GHz operation", Proc. 5th Int'l. Symp. on Space Terahertz Technology, Univ. of Michigan, p.214 (1994).

[19] M. Lindgren, M.A. Zorin, V. Trifonov, M. Danerud, D. Winkler, B.S. Karasik, G.N. Gol'tsman, and E.M. Gershenzon, "Optical mixing in a patterned $YBa_2Cu_3O_7$ thin film", Appl. Phys. Lett 65, pp.3398-3400 (1994).